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ELECTROMAGNETIC FORCES RELATED TO FLASH LAMP FAILURES IN THE NOVA/NOVETTE AMPLIFIERS

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ABSTRACT

A high rate of breakage in flashlamps destined for the Nova and Novette laser system amplifiers has prompted an investigation into the cause. Discussed herein is the possibility that electromagnetic forces (resulting from large currents in these lamps) are bending the anodes and cathodes and, thus, cracking the glass seals. Specifically, the forces resulting from these currents are approximated without indicating whether or not these forces are sufficient to break the seals. The results demonstrate that forces upto .9 N/cm (.514 lbs./in.) directed away from the reflector panel can be distributed along the anodes and cathodes. Also, the scalloped nature of the panel provides good isolation between lamps; the lamp-to-lamp forces are negligible. Time domain plots of the forces are included as well as the computer program which was developed for this investigation.

CONTENTS

INTRODUCTION

The Nova and Novette amplifiers contain panels of flash lamps which have shown a high rate of breakage in the glass stems supporting the anodes and cathodes. The breaks appear most often as cracks located on the sides closest to or farthest from the reflector on which the lamps are mounted (henceforth called the upper and lower sides). It has been suggested that these cracks are caused by electromagnetic forces resulting from the large currents in the lamps [B. Carder, 1979]. Other possible causes are thermal stresses [D. Tuft, 1974] and fire checking [D. Priest, 1975]. This investigation examines the magnetic forces in a general way using a simplified model of the refelctor panel.

System Description

A panel of flash lamps contains 40 lamps: two banks each containg 4 parallel sets of 5 series-connected lamps. The reflector is scalloped (see Figure 1) with high lips at its edges. A manifold at each end of the reflector provides support for the lamps. Figure 2 shows a typical lamp end. Figure 3 shows a sample current pulse which has a peak current of about 7KA occuring at .35ms in time. Any mechanical investigations into causes of these cracks should take note that a .35ms peak corresponds to roughly a 715Hz resonant frequency. According to Mark Kushner (personal communication) the current distribution is nearly uniform in any cross section of the plasma channel which forms within the lamp. Some computed current distributions are given in ***Xenon Flashlamp Modeling: Arc Expansion and Bore Filling*** [M. Kushner, 1983]. In addition, the radius of the plasma channel carrying the current is proportional to the current until the current reaches a maximum and then remains nearly constant thereafter (Mark Kushner, personal communication). Due to electrostatic forces, the plasma channel originates as close to the reflector as possible, i.e., at the bottom of the lamp.

Scope

In order to examine the electromagnetic forces involved, a tractable model must be used. Since only portions of the system which are good conductors interact significantly with the electromagnetic fields all other parts, for example the quartz tubing, will be neglected. Also, only those conductors directly exposed to the currents flowing in the lamps are included in any of the models considered here. This narrows the models down to just the anodes, cathodes, plasma channels, and the scalloped reflector. Still, this simplified model is beyond the scope of the desired level of effort requested for this investigation. However, by modelling the plasma channels as current sources (no plasma physics involved) and approximating the anodes and cathodes as short wires, two tractable models can be examined.

The first model replaces the scalloped reflector with a planar reflector. This model is then a good model to investigate any vertical forces which occur. As a justification of this statement consider the four parts of Figure 4 : the scallopes are first approximated by vanes, and then if these vanes were large (part c) each lamp would believe it was part of an infinite array of lamps of alternating direction above a planar reflector due to the theory of images. Conversely, the scallops could be approximated by a rippled reflector which again is close to the planar reflector. The only diffence between these two arguments is that the latter allows time delay between lamps; the former requires all currents flow simultaneously and from the same end of the lamps. Thus the latter argument is actually more appropriate since the lamps are in series. Though, it should be noted that the high lip at the edge of the reflector effectively acts as mirror to extend the panel in the manner of the first argument.

The second model accounts for the isolation which should be expected from the scalloped nature of the actual reflector. A two dimensional model of the isolation can be constructed with a single wedge located between two line currents. This model provides a good basis for examining the interaction between lamps because the tip and sloping sides of the wedge nicely approximate the peaks of the scalloped reflector.

Planar Model of Reflector

As discussed in the introduction the planar reflector is an attractive model. The most straight forward approach is to use the theory of images. The images occur symetrically about the plane of reflection with a sign change for the current flowing parallel to the plane, see Figure 5.

Channel Parameters

In developing a computer model it is imperative that the effects of various parameters are determined. Thus a code was written which required input describing the thickness and shape (bent or straight, round or elliptical) of the plasma channel which carries the current. The Appendix discusses the input and output of this code for the user. An additional model allowed the channel to grow in time until the maximum current was reached and then retained that size.

For the moment consider Figures 7, 8, 9 which show the vertical forces for the various placements of the lamps. The current channels are assumed to reside between the anode and cathode dipping down toward the reflector side of the tube. Each figure contains four plots: a solid line representing the vertical forces as modelled by a straight, thin channel; "+" 's, those modelled by a bent, thin channel; "*" 's, those modelled by a bent, thick channel (elliptical cross-section such that the channel fills most of the bottom half of the tube, see Figure 6); "#" 's, those modelled by a bent, thick channel of similar cross-section, but as a function of the current flowing through it as described earlier. Note that three of the four models give quite similar results; only the straight, thin channel is noticeably different. Because the thin channel models are roughly seven times faster than the fat channel models, the bent, thin channel model is the best to work with and will be the model incorporated in the computer program included with this report.

Height Dependence

Figure 10 combines the three previous figures to facilitate observing height dependence in the vertical forces. Note how the repulsive force increases as the lamps approach the reflector. This dependence can be approximated by

$$f_{h1}/f_{h2} = \sinh(2\pi h_2/w)/\sinh(2\pi h_1/w) \qquad (6)$$

MODELS AND RESULTS

The magnetic flux density resulting from a current source of time dependence of $j(t)$ can be written as

$$\mathbf{B}(t,\mathbf{r}) = -\mu_0/4\pi \int (c/R + \partial/\partial t)\, j(t-R/c)\, \mathbf{V}\frac{dl}{cR} \qquad (1)$$

where $\mathbf{V}$ is the vector cross product

$$\mathbf{V} = \mathbf{R}\times\mathbf{J} \qquad (2)$$

and $\mathbf{R}$ is the unit vector pointing from the source element to the field point. $\mathbf{J}$ is the direction unit vector for the current element. The parameter c is the speed of light; μ_0, the free-space permeability.

In order to examine the forces involved $j(t)$ must be specified. The difference of two exponentials can closely approximate the actual current pulse shape and can also provide for a wide range of pulse shapes (e.g., an impulse or a step function). The latter characteristic allows simple tests for computer models to verify that they are correct. Specifically, $j(t)$ was chosen to be

$$j(t) = [\exp(-\alpha t)-\exp(-\beta t)]/[\exp(-\alpha t_p)-\exp(-\beta t_p)],\ t\geq 0 \qquad (3)$$

where t_p is the time at which the maximum value occurs and the ratio (β/α) determines the ratio of the rise to fall times. Some special cases of this current pulse are

$$\text{if } \alpha=0,\ \beta=\infty \text{ then } j(t)=\text{step}(t) \qquad (4)$$

$$\text{if } \beta/\alpha=1 \text{ then } j(t)=t/t_p*\exp(1-t/t_p),\ t\geq 0 \qquad (5)$$

This second case, for t_p =.35ms, is very close to the actual current pulse.

As will be seen, the fields resulting from the current in the flash lamps are quasi-static. This is so because the dimensions involved (typically all less than one meter) and the rise/fall times (both are hundreds of microseconds) allow the fields to reach an 'unchanging' level everywhere before the lamps' currents change much.

This approximation becomes exact when the length of the tubes becomes very long and the channels are thin and straight. More specifically, the vertical force at the end of a lamp arising from an alternating, planar array of currents over a ground plane spaced w apart (figure 11) is

$$F_v = \mu_0 I^2 h/2\pi \, \Sigma_n \, (-1)^n/(4h^2+n^2w^2) = \mu_0 I^2/4w \, \mathrm{csch}(2\pi h/w) \quad (7)$$

Since F_v is for an infinite array of currents which are semi-infinite in length, the force is a poor approximation. However, the scaling as a function of h is a reasonable estimate provided it is assumed that the difference between the forces is a constant. These estimates are given by a large, dark x in Figure 10 with the force for h=.0175 used as a base value. (The constant 13N/m is added to the base value before scaling and then subtracted back out of the result.)

Figure 12 shows the effects of dipping the channel in the direction in which the forces try to push the plasma. A comparison of this figure and previous ones shows that the straight, thin channel is nearly the average of opposite dipping channels.

Forces on Reflector

The planar reflector also allows the forces on the reflector to be estimated. The vertical force is

$$\int F dx = -\mu_0 I^2/4w \, \mathrm{csch}(2\pi h/w) \quad (8)$$

where h is the distance from the reflector to the thin, straight channels. The parameter w is the spacing interval for the lamps. A plot of these forces, Figure 13, shows the exponential dependence when h/w is small. In the figure w=.03493 meters.

Lamp Delay

The horizontal force occuring cannot be accurately modelled by the planar reflector because the peaks of the scalloped reflector provide a certain level of isolation between lamps. This is discussed more fully in the next section, Wedge Approximation. With this in mind, the planar reflector model can be used to establish an absolute upper bound on the forces.

Figures 14, 15, 16 show the sideways forces as modelled by the planar reflector. In Figure 14 the delay times are just the short delays needed for the currents to flow in series through a set of lamps (typically less than a few nanoseconds). Note the small amplitudes and their small variations. These forces are down from the vertical forces by nearly $5x10^4$ (lamp separation is roughly 30cm). As the delay increases to the point when all other lamps have nearly reached their maximum current flow, the forces increase greatly to almost the level of the vertical forces (Fig. 15). **However, these forces are modelled without any isolation.** An extreme of this delay model would be the forces on an endlamp; an end lamp is essentially a lamp whose adjacent lamps to one side have infinite delay. Figure 16 shows these sideways forces which are nearly the same as those in figure 15 until the maximum. Again, these values are not representative of the physical situation at hand because neither the isolation nor the higher end scallop, which effectively acts like a ground plane to eliminate these large "last lamp" forces, are included.

Wedge Approximation

Because the reflector is scalloped and not planar there occur reflections of fields back toward each lamp. Also, fields must travel over the peaks to get to other lamps before forces can occur. The sloping sides of a wedge is a second order approximation to the scalloped shape (a vertical vane would be a first order approximation which is a limiting case of the wedge). Though little insight can be gained from examining the fields between two wedges without great difficulty, a qualitative approach can provide much.

Consider the situation of Figure 17. If the current is centered the paths available for a field to propagate along and be reflected back to the lamp can be symmetrically imaged to obtain equally valid paths. This symmetric set of paths can not create any vertical **B** field. Consequently, there are no sideways forces. Indeed, this same observation could be made for the scalloped reflector. Putting this another way, the only sideways forces are from the adjacent lamps' currents provided the lamp of concern is nearly centered in its trough.

Isolation

Lamp to lamp interactions are impeded to a certain level by the scalloped peaks which penetrate the regions between lamps. If the height of the peaks were great enough the field from one lamp would never get to the next. Conversely, if there were no peaks the field would not be impeded at all. However, the situation at hand is some where in between and, thus, a planar reflector is not a good model for isolation.

To accurately model the isolation occurring both the height and shape of the peaks need to be considered. A wedge is a good approximation. Figure 18 depicts the model and its parameters h, φ_0, and α. Since the forces are proportional to the magnetic flux (call this field $\mathbf{B}_1$ eminating from current $\mathbf{I}_1$) only $\mathbf{B}_1$ needs to be examined. The magnetic flux from $\mathbf{I}_1$ at $\mathbf{I}_2$ is

$$\mathbf{B}_1(\mathbf{I}_2) = -\mu_0 I/8\pi w \tan(\varphi_0/2)\{(\mathbf{x}h+\mathbf{y}w)/(1+h^2/w^2)\} \qquad (9)$$

Note that when $\varphi_0 = 90°$ (i.e., h=0.0) then $\mathbf{B}_1$ has no vertical component and, consequently, $\mathbf{I}_2 \times \mathbf{B}_1$ gives no sideways forces. Furthermore, the resulting force is in the opposite direction as the total force when modelled by the planar reflector (and not accounted for in that model). This obsevation that, in addition to no sideways forces, the vertical forces are decreased indicates that the planar model provides an upper limit on the vertical forces. Equation 9 can be used to estimate the isolation for any desired values of h, α, φ_0.

SUMMARY

Two tractable models have provided information on vertical and horizontal forces on the anodes and cathodes of the flash lamps. The planar model, including the computer code, provides an excellent means of examining the vertical forces and, with some care, can be used to establish bounds on the lateral forces. In addition, it has provided a setting in which to examine the effects of lamp to reflector distance, plasma channel radius, and channel dip.

The wedge approximation has shown that the peaks of the scallops create a high level of isolation between lamps. Thus the electromagnetic forces are almost entirely vertical. Furthermore, these vertical forces can be as large as 90 N/m (.514 lbs./in.) for 7KA peak currents.

Suggestions

The equations and code contained within this report can be used to further investigate these electromagnetic forces. Two significant applications would be: using the vertical forces from the code as a uniformly distributed load on the anodes/cathodes to establish whether or not these forces are sufficient in magnitude and close enough in resonance (.35ms peak corresponds to roughly 715Hz) to cause cracking; second, using the wedge approximation to identify possible reflector shape modifications (raise/lower the height of the peak) to reduce these forces.

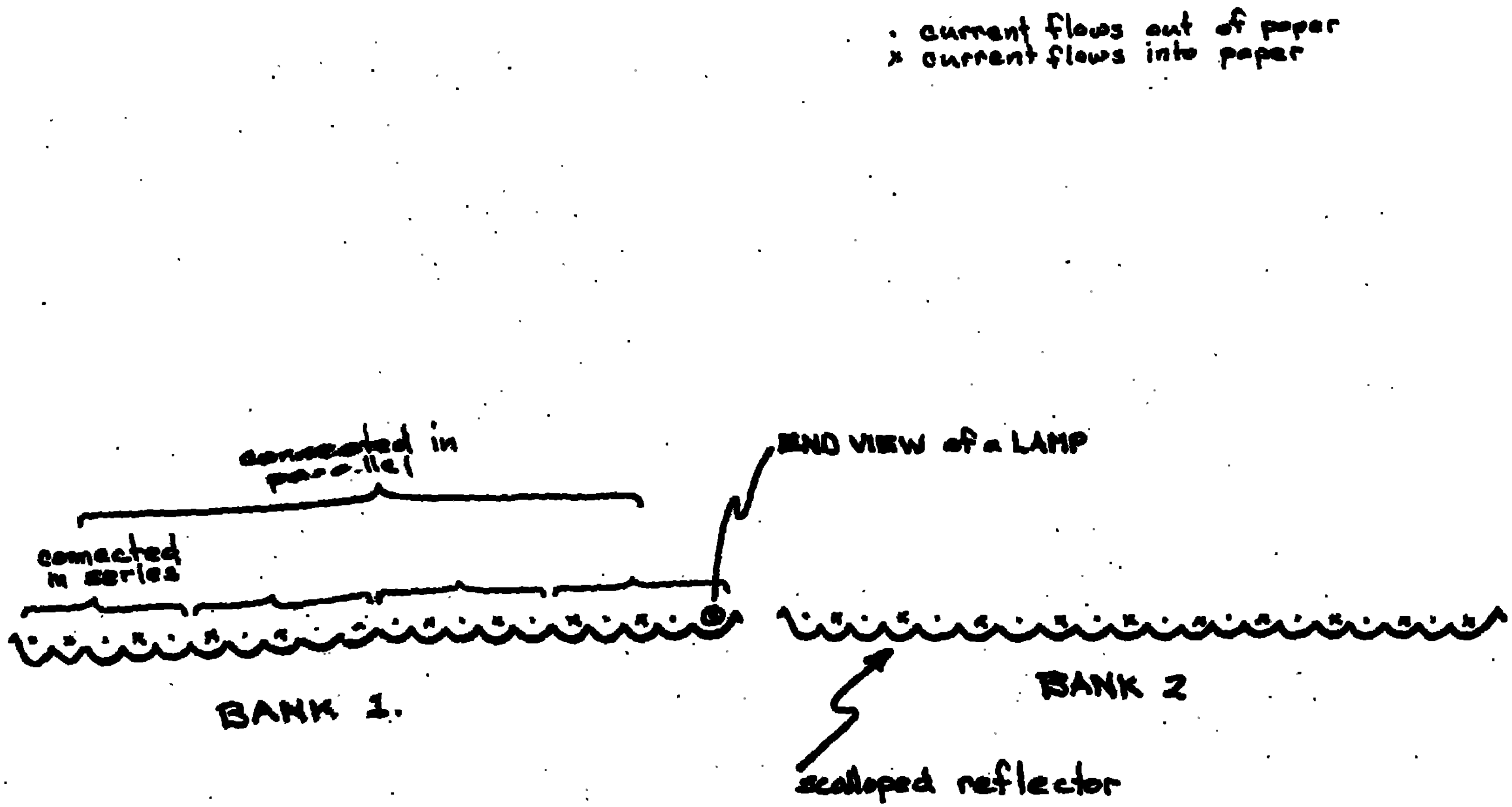


Figure 1. The scalloped reflector.

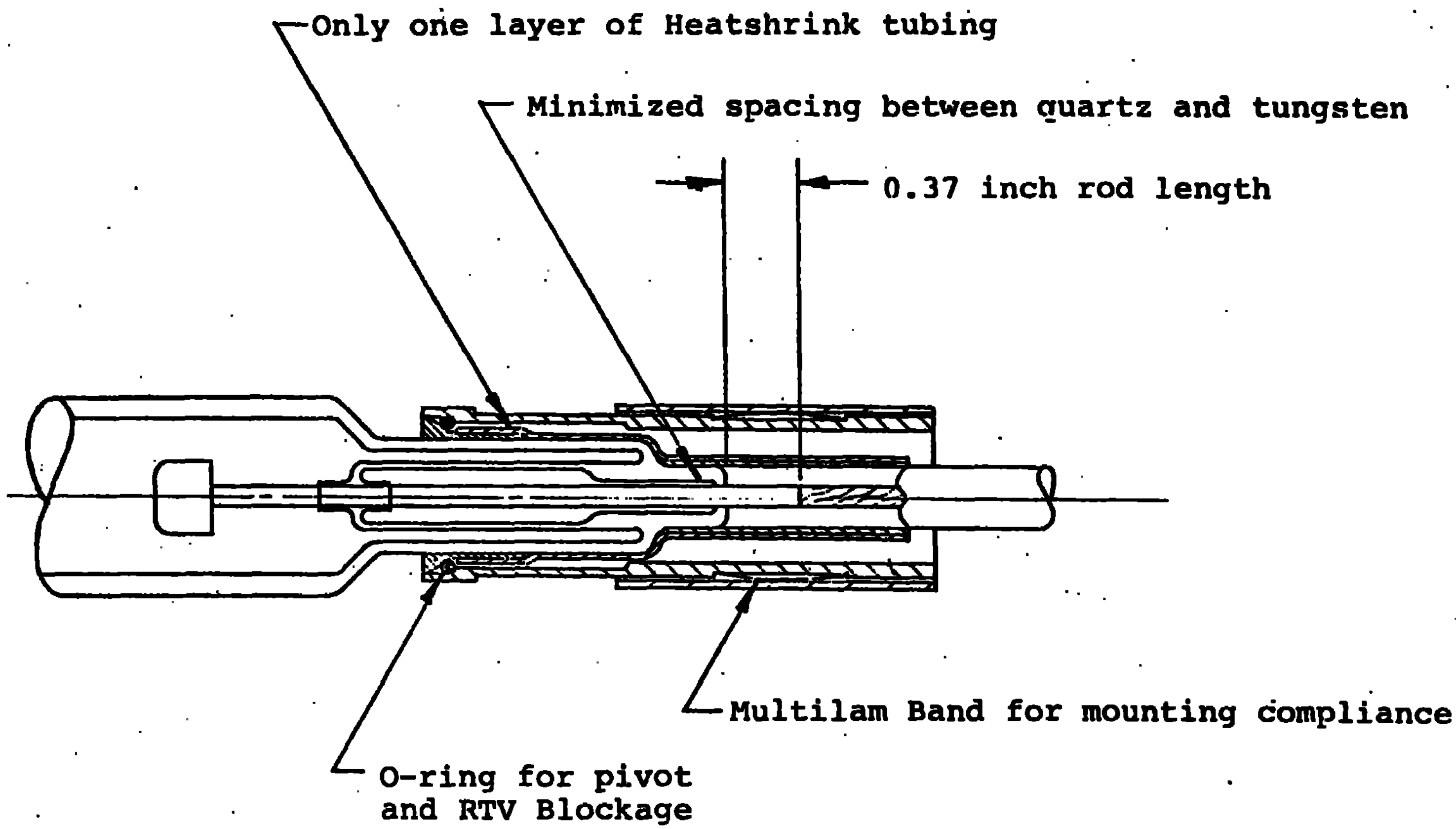
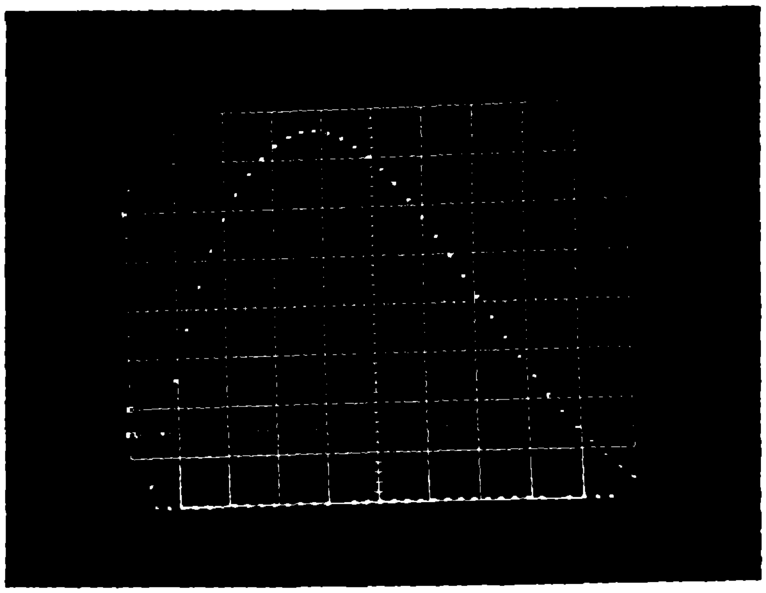


Figure 2. Typical lamp end. Items 12 and 13

7KA peak



.1 ms/div

Figure 3. Sample current pulse which drives the lamps.

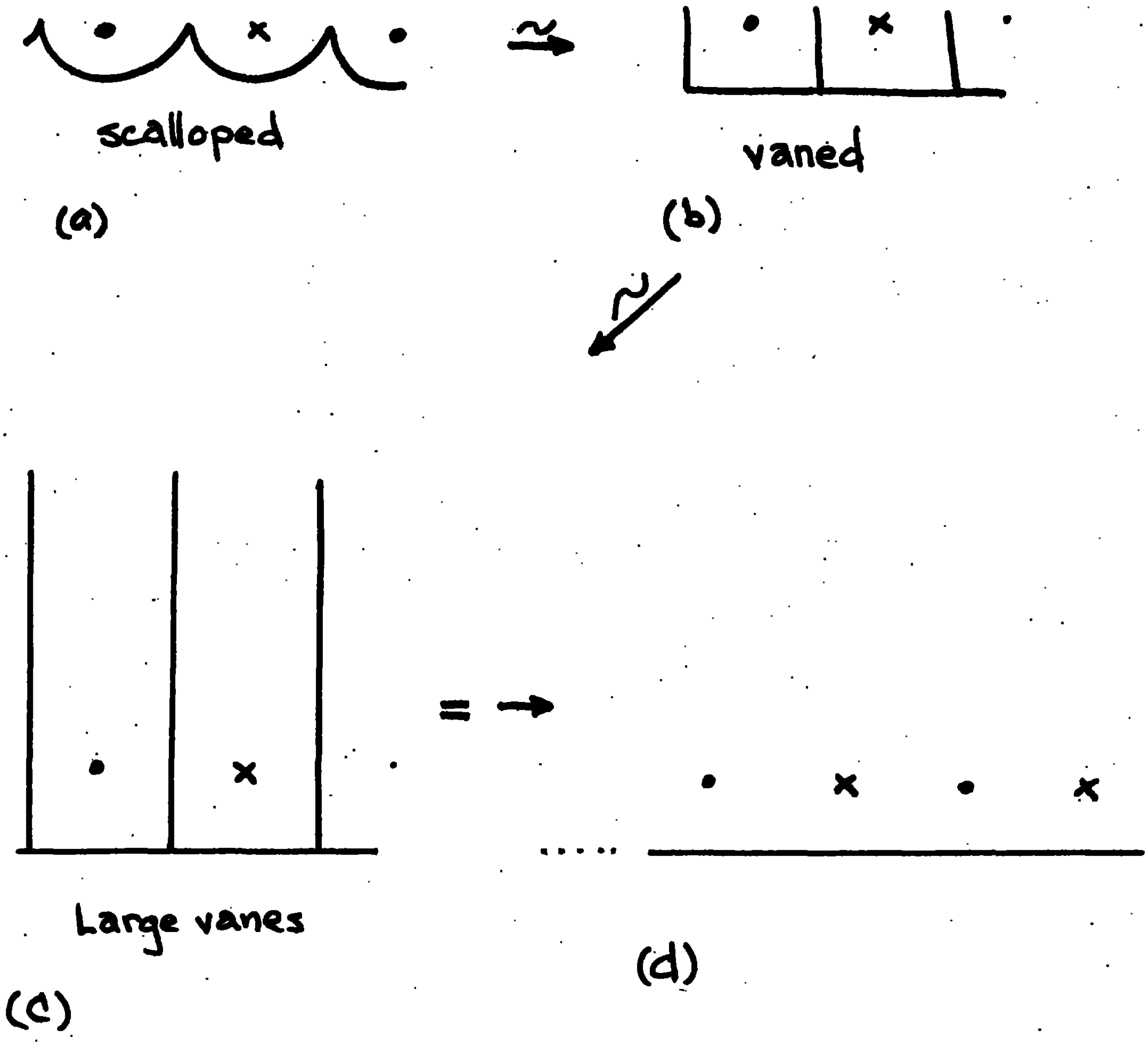


Figure 4. Planar approximation to the scalloped reflector.

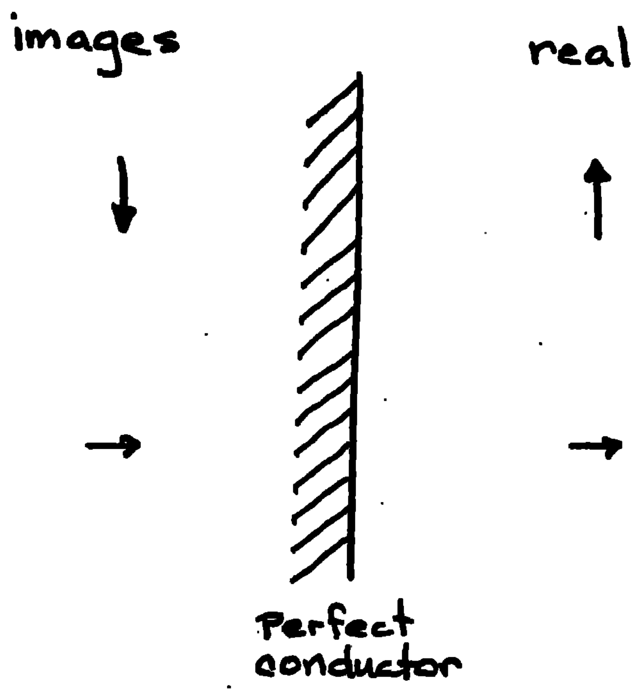


Figure 5. Currents and their images.

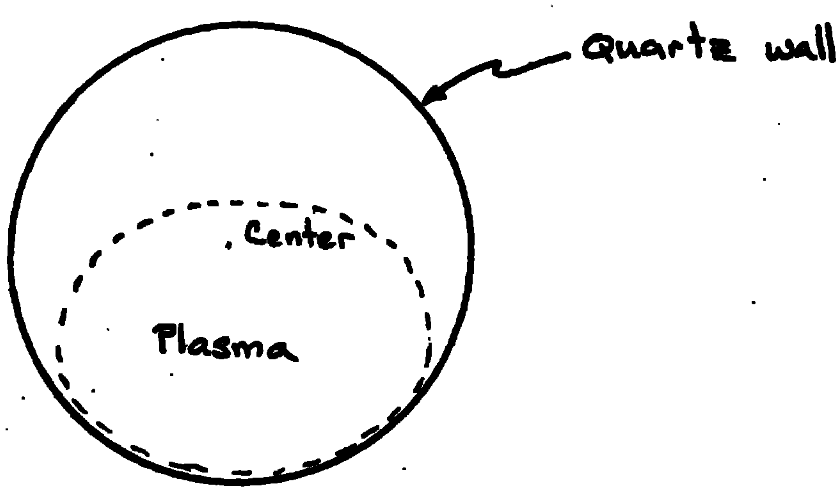


Figure 6. Cross-section of a current channel.

LAMPS AT .0125M ABOVE REFLECTOR, CHANNELS DIP TO .0068

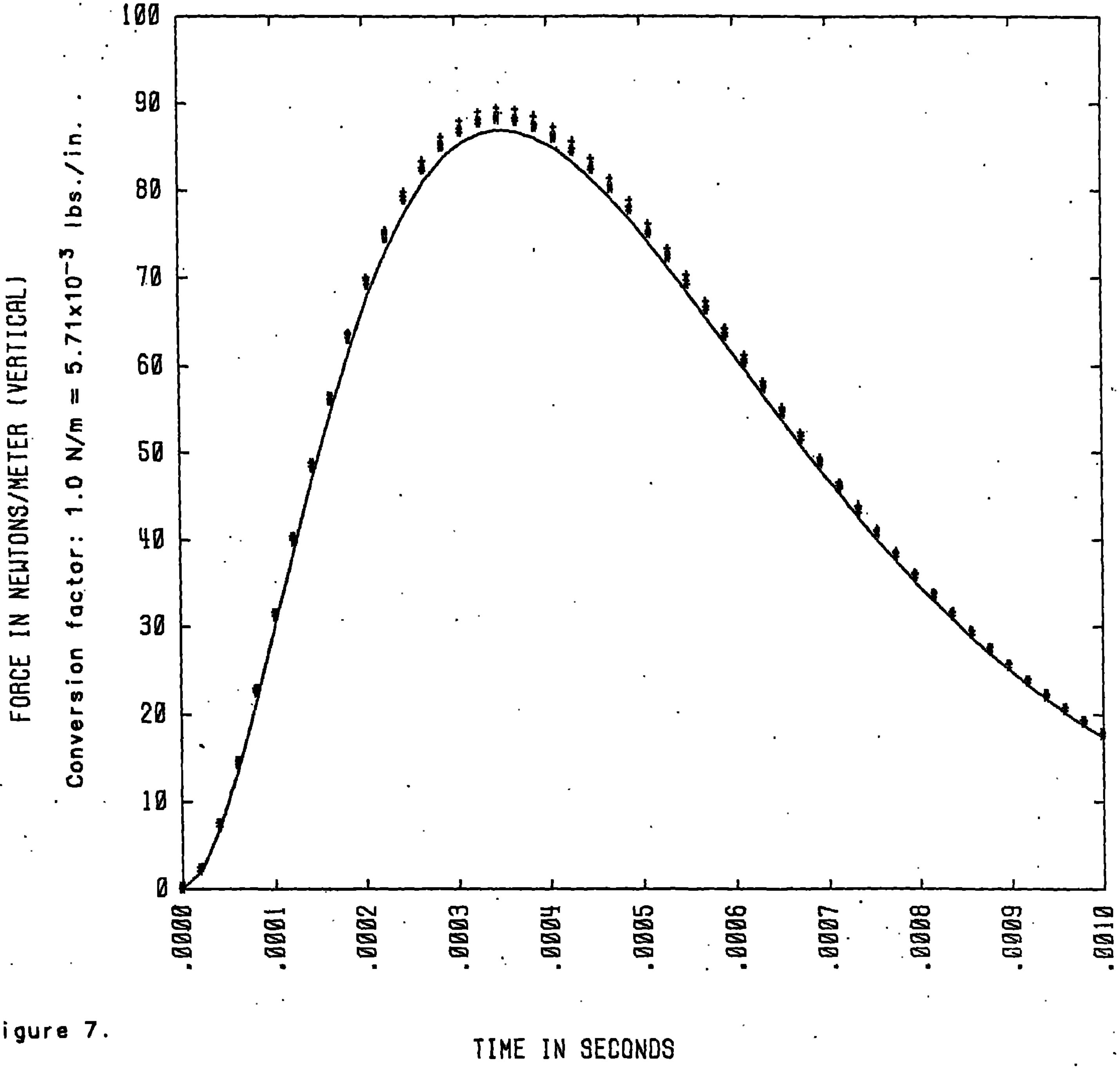


Figure 7.

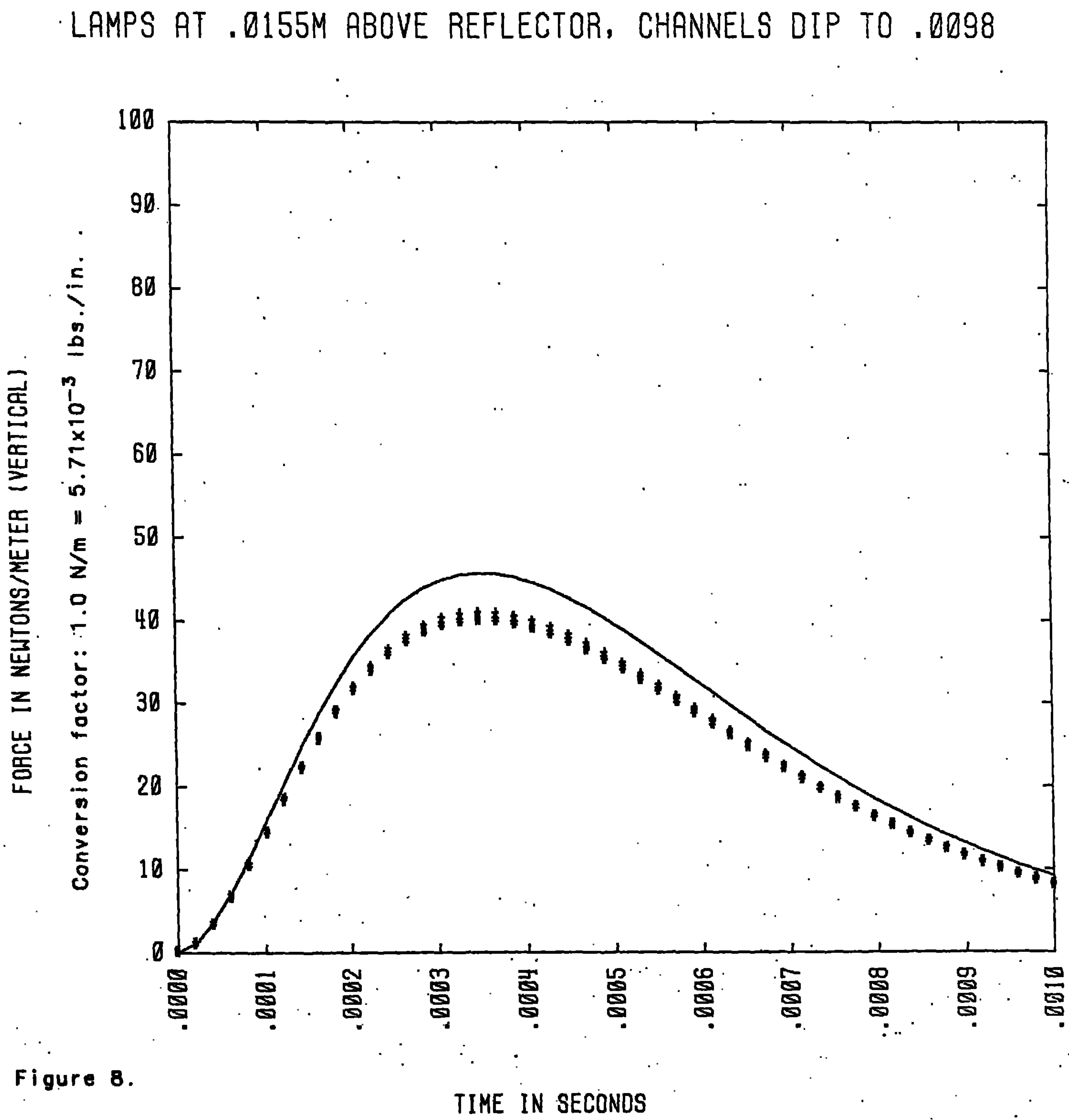

LAMPS AT .0155M ABOVE REFLECTOR, CHANNELS DIP TO .0098
FORCE IN NEWTONS/METER (VERTICAL)
Conversion factor: 1.0 N/m = 5.71x10^{-3} lbs./in.
100
90
80
70
60
50
40
30
20
10
0
.0000
.0001
.0002
.0003
.0004
.0005
.0006
.0007
.0008
.0009
.0010
TIME IN SECONDS

Figure 8.

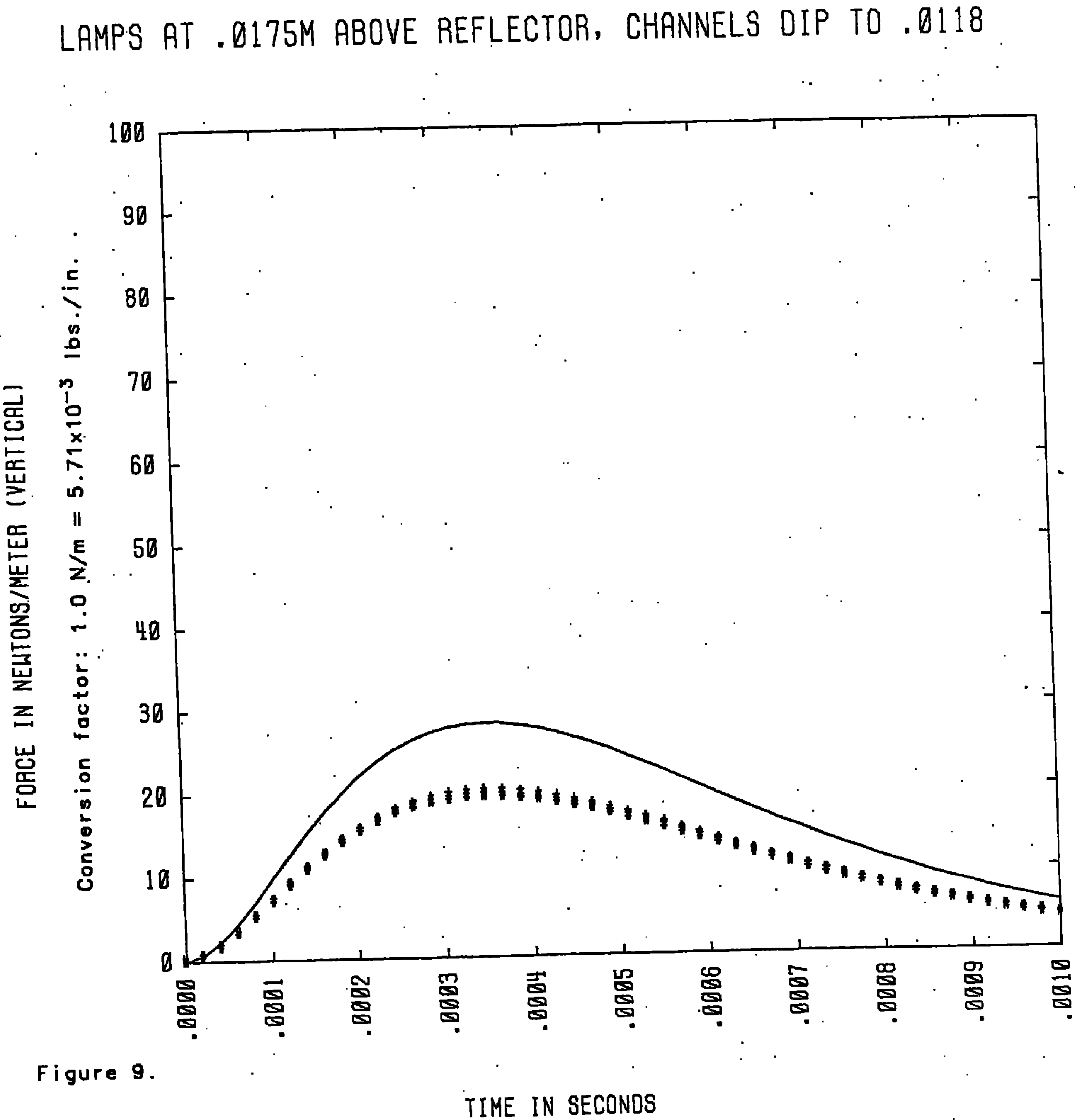

LAMPS AT .0175M ABOVE REFLECTOR, CHANNELS DIP TO .0118
FORCE IN NEWTONS/METER (VERTICAL)
Conversion factor: 1.0 N/m = 5.71x10^-3 lbs./in.
0
10
20
30
40
50
60
70
80
90
100
.0000
.0001
.0002
.0003
.0004
.0005
.0006
.0007
.0008
.0009
.0010
TIME IN SECONDS

Figure 9.

LAMP AND DIP HEIGHTS: .0125,.0068; .0155,.0098; .0175,.0118

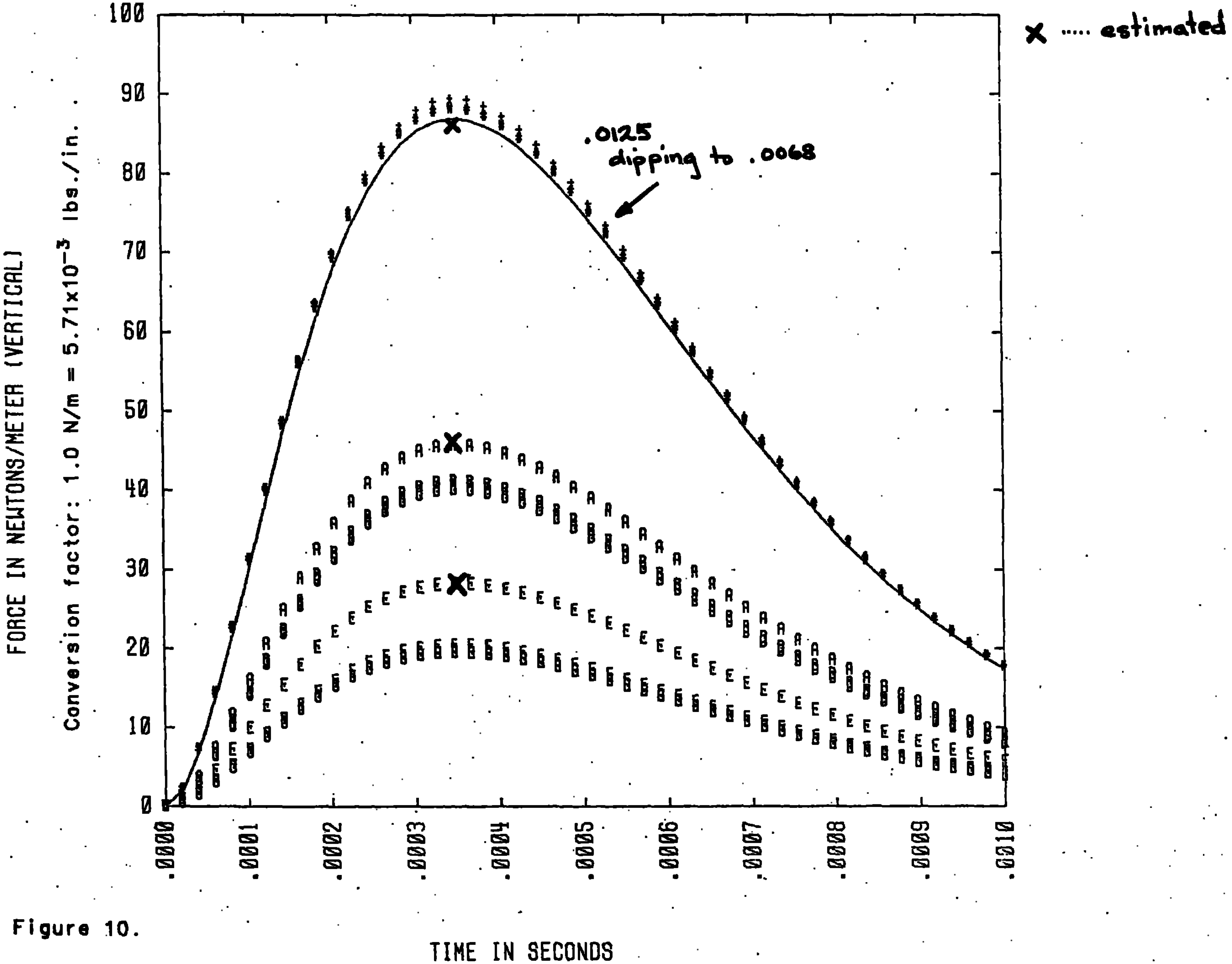


Figure 10.

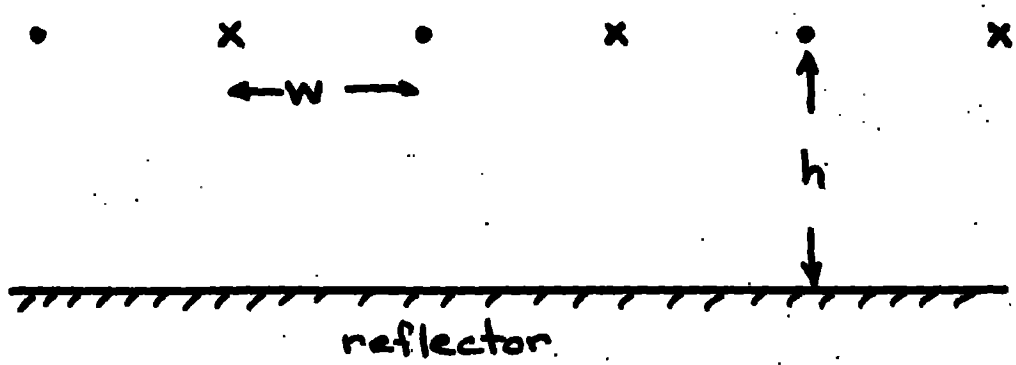


Figure 11. Planar array of currents over a ground plane.

LAMP AND DIP HEIGHTS: .0125,.0182; .0155,.0212; .0175,.0232

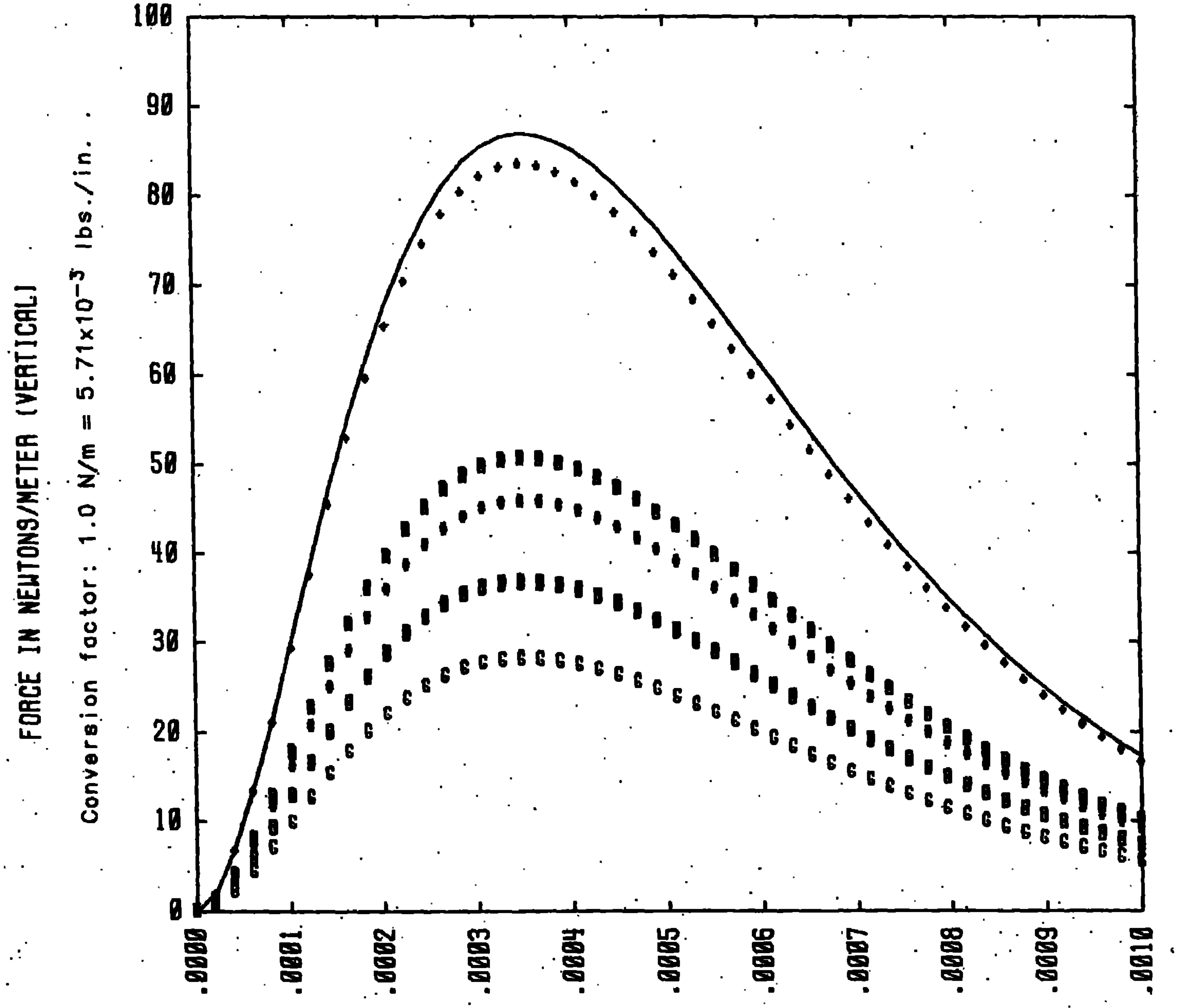


Figure 12.

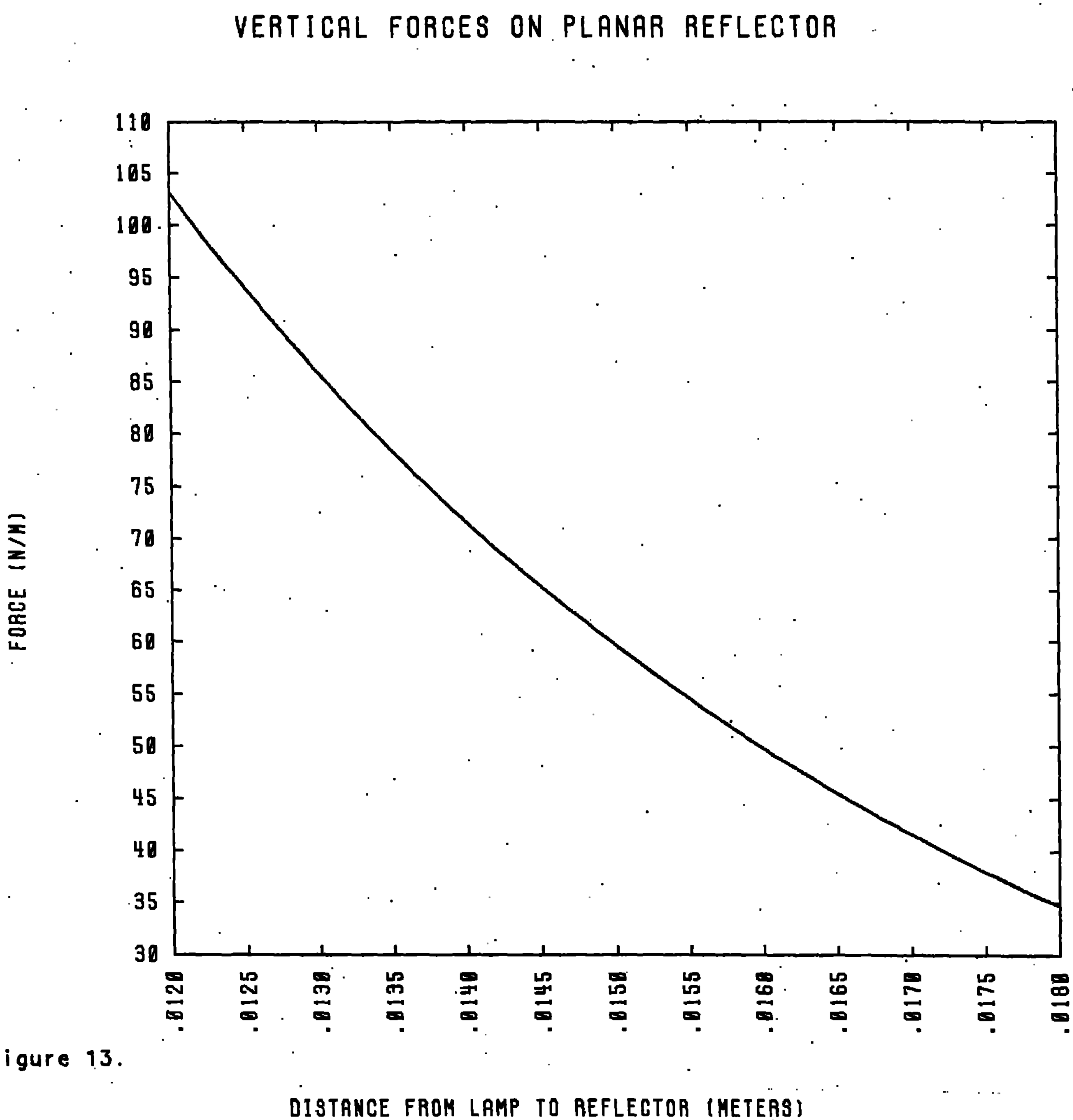

VERTICAL FORCES ON PLANAR REFLECTOR
FORCE (N/M)
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
.0120
.0125
.0130
.0135
.0140
.0145
.0150
.0155
.0160
.0165
.0170
.0175
.0180
DISTANCE FROM LAMP TO REFLECTOR (METERS)

Figure 13.

LAMP AND DIP HEIGHTS: .0125,.0068; .0155,.0098; .0175,.0118

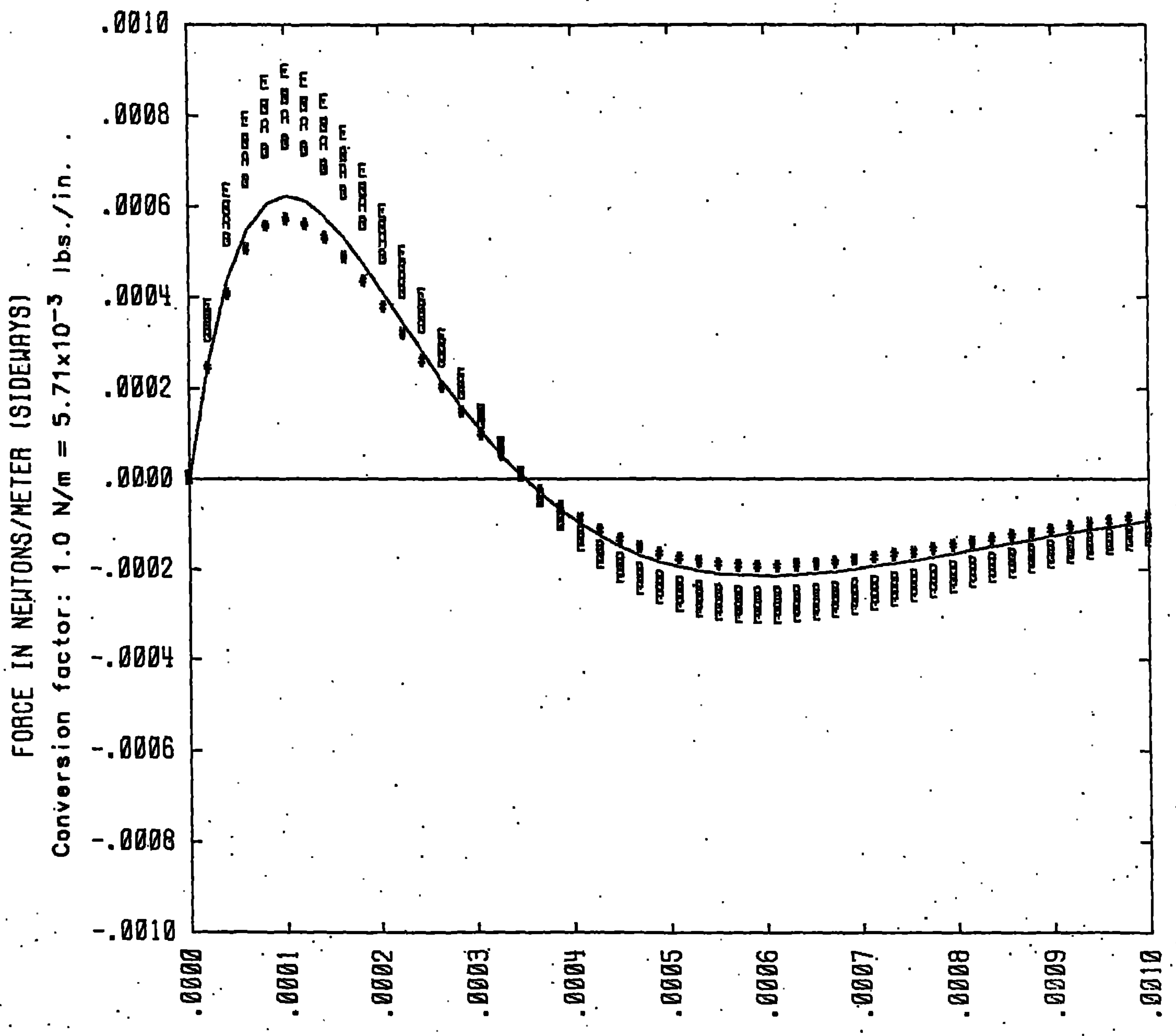


Figure 14.

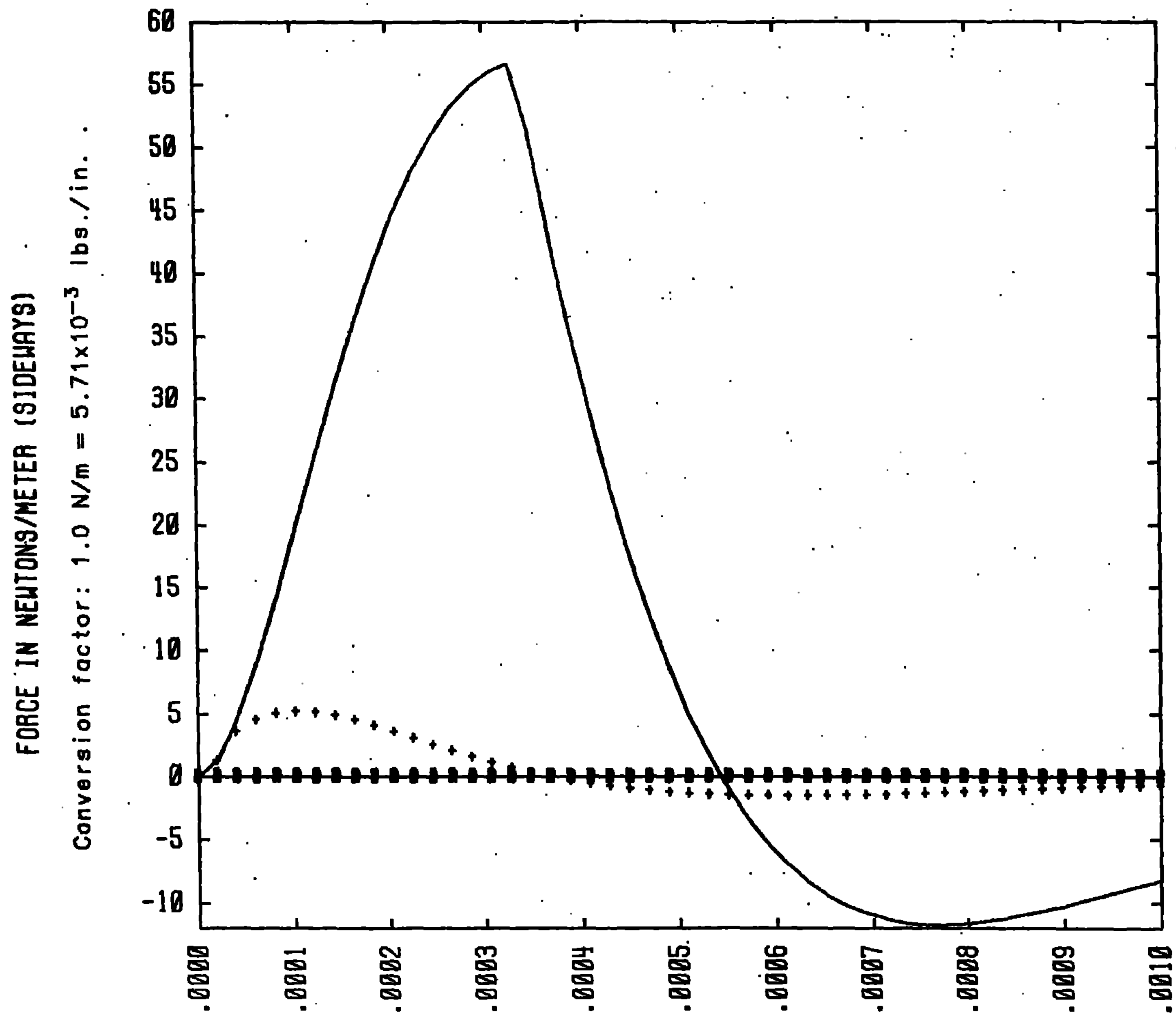

LAMP DELAYS OF 0., .33E(N) N--7,-6,-5,-4,-3 SECONDS
FORCE IN NEWTONS/METER (SIDEWAYS)
Conversion factor: 1.0 N/m = 5.71x10^{-3} lbs./in.
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
.0000
.0001
.0002
.0003
.0004
.0005
.0006
.0007
.0008
.0009
.0010
TIME IN SECONDS

Figure 15.

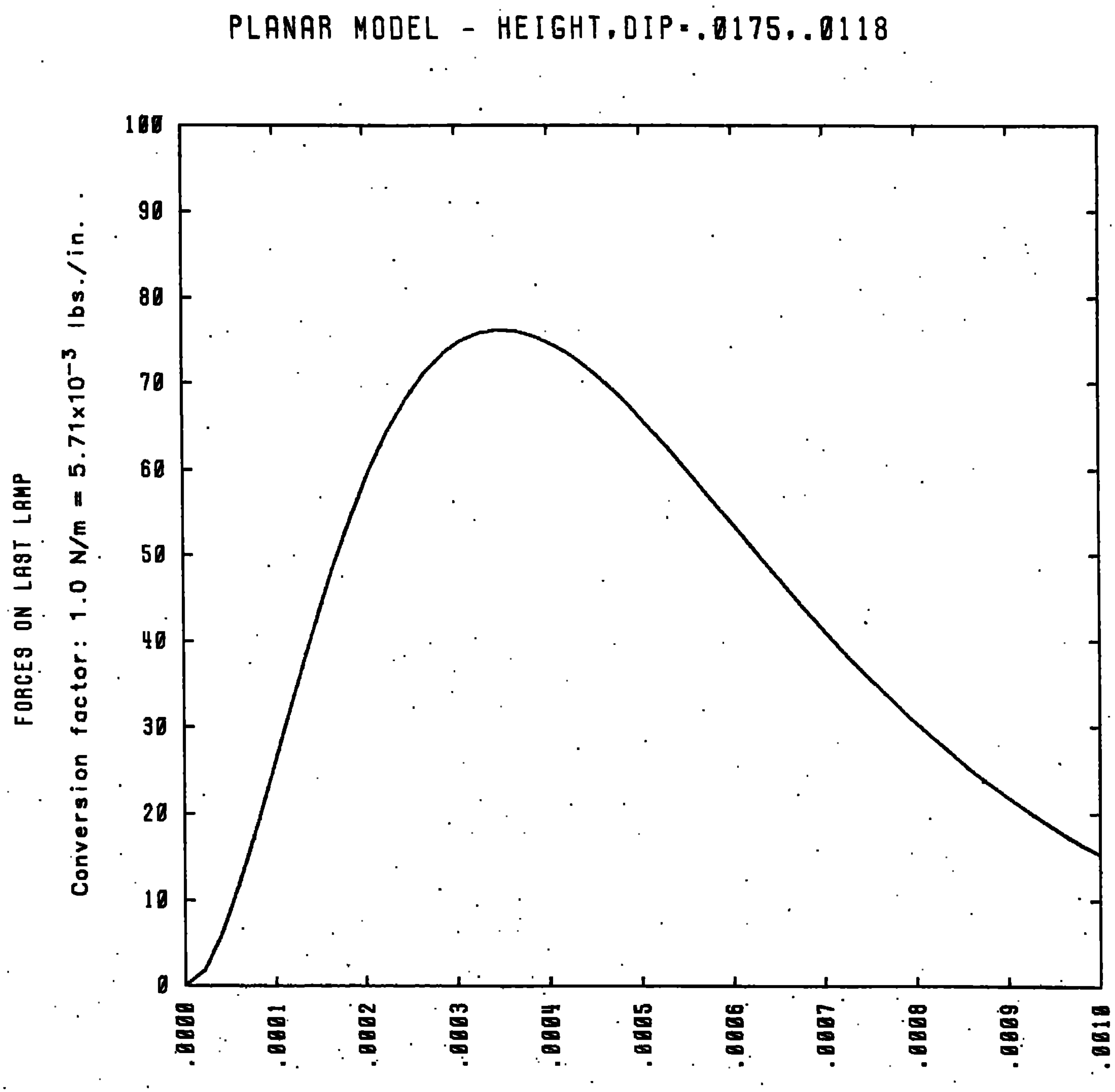

PLANAR MODEL - HEIGHT,DIP=.0175,.0118
FORCES ON LAST LAMP
Conversion factor: 1.0 N/m = 5.71x10^{-3} lbs./in.
0
10
20
30
40
50
60
70
80
90
100
.0000
.0001
.0002
.0003
.0004
.0005
.0006
.0007
.0008
.0009
.0010
TIMES IN SECONDS

Figure 16.

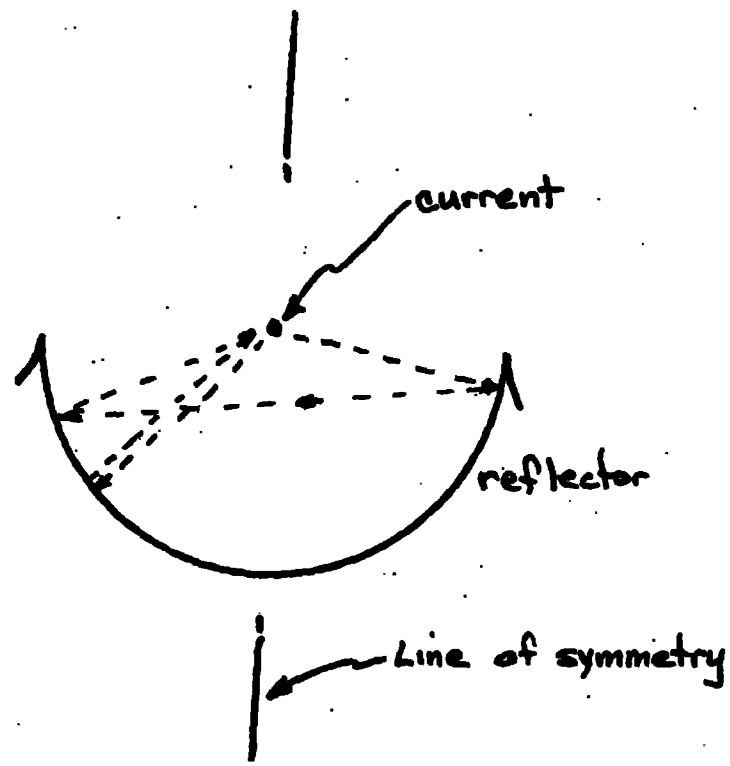


Figure 17. Paths of reflection.

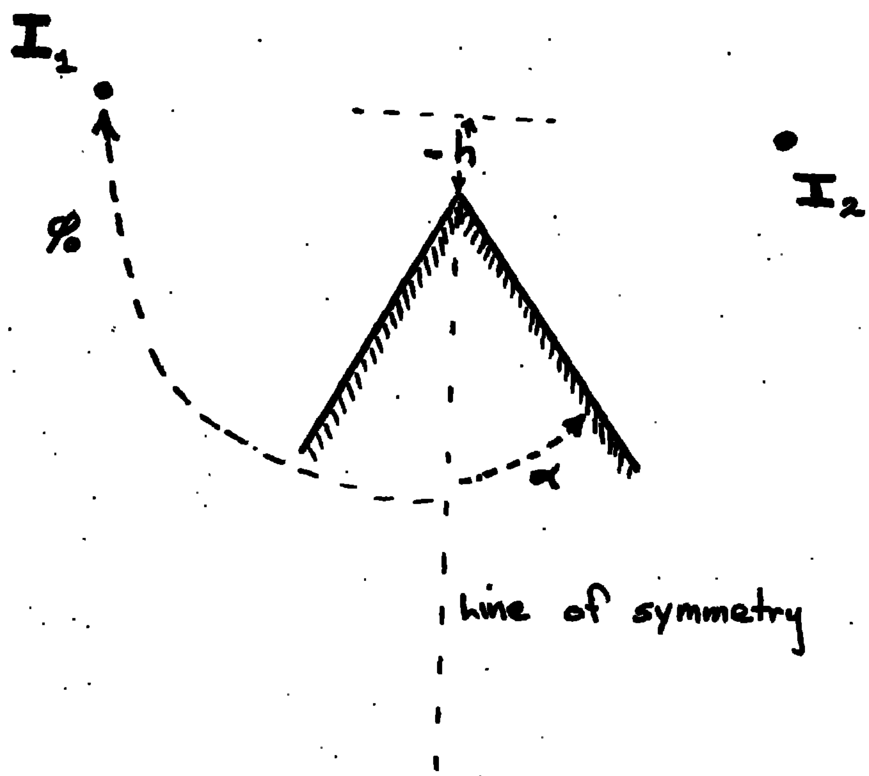


Figure 18. Wedge approximation of the scallop's peak.

REFERENCES

Carder, B. (May 15, 1979), "Forces on Flashlamps (revisited)," LLNL interdepartment letter EE #79-77, 0049a, file 44.

Kushner, Mark J. (March 17, 1983), "Xenon Flashlamp Modeling: Arc Expansion and Bore Filling," LLNL Rcd #83-126/3138k.

Priest, David k. (October, 1975), "Flashlamp Infant Mortality Study," Report no. R-ILC-75-8, ILC Technology, 164 Commercial Street, Sunnyvale, California 94086.

Tuft, Dean b. (March 11, 1974), "Stress in High Energy Flashlamp Envelopes," LLNL UCID-16861.

APPENDIX

Computer Code

The following table lists the available input parameters and their defaults. The form of the input deck is a namelist.

parameter	default values	definition
tpeak	.35e-3	t_p
ratio	1.0001	β/α
tstart	0.0	time to start calculations
tstop	1.0e-3	time to stop calculations
ntimes	50	number of time points to compute at
xend	.237	position of lamp ends (.5 lamp length)
xdip	.180	coordinate between which channel is straight
yspace	.03493	lamp spacing interval
zhght	.0180	height from reflector to lamp's center
dip	.0057	depth of dip toward reflector
nleft	0	number of lamps to left of lamp
nright	0	number of lamps to the right
nsteps	80	number of integration intervals on each lamp
delayd(n)	0.	effective distance before current gets to lamp 'n'— 3.e8m gives a one second delay relative to t=0.0 . n=1 is lefthand lamp.

The following is a sample input deck which generated the output on the next page.

```
$nl01
zhght=.0125,
dip=.0057,
nleft=3,nright=3,
delayd= -2.94,-1.96,-.98,0.0,.98,1.96,2.94,
$endnl01
```

The following is a sample output with the input parameters echoed back before any computations take place.

```
$nl01
 tpeak  =    3.5000000000000e-04,
 ratio  =    1.0001000000000e+00,
 tstart =    0.                 ,
 tstop  =    1.0000000000000e-03,
 ntimes =        50,
 xend   =    2.3700000000000e-01,
 xdip   =    1.8000000000000e-01,
 yspace =    3.4930000000000e-02,
 zhght  =    1.2500000000000e-02,
 dip    =    5.6999999999999e-03,
 nleft  =         3,
 nright =         3,
 nsteps =        80,
 delayd =   -2.9400000000000e+00,   -1.9600000000000e+00,
            -9.7999999999999e-01,    0.                 ,
             9.7999999999999e-01,    1.9600000000000e+00,
             2.9400000000000e+00,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
             0.                 ,    0.                 ,
$end


lamps between +/-   .2370000  (straight between +/-   .1800000)
      spaced by    .0349300
 at  .0125000 above reflector and dipping down to  .0068000
there are   7 lamps,  3 to the left and   3 to the right
the current pulse is a double exponential
      with t1/t2=   .100e+01 and its maximum at t=  .35000e-03


  anode
 r0=(  .23700e+00, 0.          ,  .12500e-01)
 dr0=( -.98058, 0.00000, -.19612)
 time(seconds)              force in x    force in y     force in z
 ============               ==========    ==========     ==========
  0.                         0.            0.             0.
   .20408e-04               -.81587e-08    .49428e-11     .40793e-07
   .40816e-04               -.29041e-07    .82527e-11     .14521e-06
```

.61224e-04	-.58149e-07	.10289e-10	.29074e-06
.81633e-04	-.91996e-07	.11346e-10	.45998e-06
.10204e-03	-.12792e-06	.11662e-10	.63960e-06
.12245e-03	-.16393e-06	.11429e-10	.81964e-06
.14286e-03	-.19856e-06	.10802e-10	.99282e-06
.16327e-03	-.23080e-06	.99034e-11	.11540e-05
.18367e-03	-.25995e-06	.88313e-11	.12998e-05
.20408e-03	-.28560e-06	.76611e-11	.14280e-05
.22449e-03	-.30754e-06	.64507e-11	.15377e-05
.24490e-03	-.32571e-06	.52441e-11	.16286e-05
.26531e-03	-.34018e-06	.40741e-11	.17009e-05
.28571e-03	-.35110e-06	.29638e-11	.17555e-05
.30612e-03	-.35868e-06	.19288e-11	.17934e-05
.32653e-03	-.36318e-06	.97938e-12	.18159e-05
.34694e-03	-.36487e-06	.12083e-12	.18243e-05
.36735e-03	-.36403e-06	-.64484e-12	.18201e-05
.38776e-03	-.36095e-06	-.13184e-11	.18048e-05
.40816e-03	-.35592e-06	-.19027e-11	.17796e-05
.42857e-03	-.34921e-06	-.24017e-11	.17461e-05
.44898e-03	-.34107e-06	-.28208e-11	.17054e-05
.46939e-03	-.33175e-06	-.31656e-11	.16588e-05
.48980e-03	-.32146e-06	-.34421e-11	.16073e-05
.51020e-03	-.31041e-06	-.36567e-11	.15521e-05
.53061e-03	-.29879e-06	-.38154e-11	.14939e-05
.55102e-03	-.28675e-06	-.39245e-11	.14337e-05
.57143e-03	-.27443e-06	-.39896e-11	.13722e-05
.59184e-03	-.26198e-06	-.40161e-11	.13099e-05
.61224e-03	-.24950e-06	-.40093e-11	.12475e-05
.63265e-03	-.23709e-06	-.39739e-11	.11854e-05
.65306e-03	-.22482e-06	-.39140e-11	.11241e-05
.67347e-03	-.21277e-06	-.38339e-11	.10639e-05
.69388e-03	-.20100e-06	-.37371e-11	.10050e-05
.71429e-03	-.18955e-06	-.36267e-11	.94777e-06
.73469e-03	-.17847e-06	-.35057e-11	.89233e-06
.75510e-03	-.16777e-06	-.33766e-11	.83883e-06
.77551e-03	-.15748e-06	-.32416e-11	.78740e-06
.79592e-03	-.14762e-06	-.31027e-11	.73809e-06
.81633e-03	-.13819e-06	-.29616e-11	.69096e-06
.83673e-03	-.12921e-06	-.28197e-11	.64603e-06
.85714e-03	-.12066e-06	-.26783e-11	.60331e-06
.87755e-03	-.11255e-06	-.25384e-11	.56277e-06
.89796e-03	-.10488e-06	-.24010e-11	.52439e-06
.91837e-03	-.97624e-07	-.22666e-11	.48812e-06
.93878e-03	-.90782e-07	-.21360e-11	.45391e-06
.95918e-03	-.84340e-07	-.20095e-11	.42170e-06
.97959e-03	-.78284e-07	-.18876e-11	.39142e-06
.10000e-02	-.72600e-07	-.17704e-11	.36300e-06

cathode
r0=(-.23700e+00, 0.   ,   .12500e-01)
dr0=(-.98058, 0.00000,   .19612)

time(seconds)	force in x	force in y	force in z
-.15811e-08	0.	0.	0.
.20407e-04	.81560e-08	.49423e-11	.40780e-07
.40815e-04	.29037e-07	.82522e-11	.14518e-06
.61223e-04	.58143e-07	.10289e-10	.29072e-06
.81631e-04	.91990e-07	.11346e-10	.45995e-06
.10204e-03	.12791e-06	.11661e-10	.63957e-06
.12245e-03	.16392e-06	.11428e-10	.81961e-06
.14286e-03	.19856e-06	.10801e-10	.99279e-06
.16326e-03	.23080e-06	.99032e-11	.11540e-05
.18367e-03	.25995e-06	.88311e-11	.12997e-05
.20408e-03	.28560e-06	.76609e-11	.14280e-05
.22449e-03	.30754e-06	.64505e-11	.15377e-05
.24490e-03	.32571e-06	.52441e-11	.16285e-05
.26530e-03	.34018e-06	.40740e-11	.17009e-05
.28571e-03	.35110e-06	.29635e-11	.17555e-05
.30612e-03	.35868e-06	.19287e-11	.17934e-05
.32653e-03	.36318e-06	.97929e-12	.18159e-05
.34694e-03	.36487e-06	.12083e-12	.18243e-05
.36735e-03	.36403e-06	-.64492e-12	.18201e-05
.38775e-03	.36095e-06	-.13185e-11	.18048e-05
.40816e-03	.35592e-06	-.19028e-11	.17796e-05
.42857e-03	.34921e-06	-.24018e-11	.17461e-05
.44898e-03	.34107e-06	-.28209e-11	.17054e-05
.46939e-03	.33175e-06	-.31656e-11	.16588e-05
.48979e-03	.32147e-06	-.34421e-11	.16073e-05
.51020e-03	.31042e-06	-.36567e-11	.15521e-05
.53061e-03	.29879e-06	-.38154e-11	.14939e-05
.55102e-03	.28675e-06	-.39245e-11	.14337e-05
.57143e-03	.27444e-06	-.39895e-11	.13722e-05
.59184e-03	.26198e-06	-.40161e-11	.13099e-05
.61224e-03	.24950e-06	-.40093e-11	.12475e-05
.63265e-03	.23709e-06	-.39738e-11	.11854e-05
.65306e-03	.22482e-06	-.39140e-11	.11241e-05
.67347e-03	.21278e-06	-.38339e-11	.10639e-05
.69388e-03	.20100e-06	-.37371e-11	.10050e-05
.71428e-03	.18956e-06	-.36268e-11	.94778e-06
.73469e-03	.17847e-06	-.35057e-11	.89234e-06
.75510e-03	.16777e-06	-.33766e-11	.83884e-06
.77551e-03	.15748e-06	-.32416e-11	.78740e-06
.79592e-03	.14762e-06	-.31027e-11	.73810e-06
.81632e-03	.13819e-06	-.29616e-11	.69097e-06
.83673e-03	.12921e-06	-.28197e-11	.64604e-06
.85714e-03	.12066e-06	-.26783e-11	.60331e-06
.87755e-03	.11256e-06	-.25385e-11	.56278e-06
.89796e-03	.10488e-06	-.24010e-11	.52439e-06
.91837e-03	.97625e-07	-.22666e-11	.48812e-06
.93877e-03	.90783e-07	-.21360e-11	.45391e-06
.95918e-03	.84341e-07	-.20095e-11	.42170e-06
.97959e-03	.78285e-07	-.18876e-11	.39142e-06
.10000e-02	.72601e-07	-.17704e-11	.36300e-06

```
      program nova
c=====================================================================
c
c      #                                   #
c       #                                 # #
c       #   ##    ###   ###  # ##         #    ###  # ##   ###   ###
c       #  #  #  #     #   # ##  #       ###  #   # ##  # #   # #   #
c       #   ###   ###  ##### #            #   #   # #     #     #####
c       #  #  #      # #     #            #   #   # #     #     #
c       #  #  #  #   # #   # #            #   #   # #     #   # #   #
c        #  ## #  ###   ###  #            #    ###  #      ###   ###
c
c
c
c---------------------------------------------------------------------
      dimension simp(3),bfield(3),force(3,512),ftotal(512),t(512)
      dimension delayd(30)
      external intgrnd
      common /intgrl/ sdelta,x0,y0,z0,n,time
      common /path/ nleft,nright,xend,xdip,yspace,zhght,zdip,delayd
      common /source/ t1,t2,peak,c
      data pi,c/3.141592654,2.997925e8/
      data tpeak,ratio,tstart,tstop,ntimes/.35e-3,1.0001,0.,.001,50/,
     1 xend,xdip,yspace,zhght,dip/.237,.180,.03493,.018,.006/,
     2 nleft,nright,nsteps,delayd/2,2,80,-1.96,-.98,0.,.98,1.96,25*0./
c
      call link("unit5=(input,open),unit6=(output,text,create)//")
c     ---------------
c                         read in the system parameters
      namelist /nl01/ tpeak,ratio,tstart,tstop,ntimes,
     1 xend,xdip,yspace,zhght,dip,nleft,nright,nsteps,delayd
      read(5,nl01)

      zdip=zhght-dip
      ntotal=1+nleft+nright
      nsteps=2*int(nsteps/2.)
      sstart=0.
      sstop=2.*xend
      sdelta=(sstop-sstart)/float(nsteps)
c                interpret tpeak,ratio into t1,t2,peak (i.e. normalize)
      t1=tpeak*(ratio-1.)/alog(ratio)
      t2=t1/ratio
      peak=1./( exp(-tpeak/t1) - exp(-tpeak/t2) )
      write(6,nl01)
      write(6,201) xend,xdip,yspace,zhght,zdip,
     1  (nleft+nright+1),nleft,nright
      write(6,301) ratio,tpeak
  201 format(///,1x,"lamps between +/-",f10.7,
     1   "  (straight between +/-",f10.7,")",/
     2   7x,"spaced by ",f10.7,/,"  at",f10.7," above reflector",
     3   " and dipping down to",f10.7,/
     4   1x,"there are ",i3," lamps,",i3," to the left and ",
```

```
     5   i3," to the right" )
  301 format( 1x,"the current pulse is a double exponential",/
     1        7x,"with t1/t2=",e11.3," and its maximum at t=",e12.5)
c                          initialize time points
      do 10 loop=1,ntimes
      t(loop)=tstart+(loop-1.)*tstop/(ntimes-1.)
   10 continue
c                       choose field point on n=0 lamp
      id=" anode  "
      do 80 n0=1,2
      s0=(n0-1.)*2.*xend
      call rn(0,s0,delayn0,x0,y0,z0,dx0,dy0,dz0)
      write(6,202) id,x0,y0,z0,dx0,dy0,dz0
  202 format( //,3x,a8,/,3x,"r0=(",e12.5,",",e12.5,
     1   ",",e12.5,")",/,3x,"dr0=(",f8.5,",",f8.5,",",f8.5,")",
     2 /,3x,"time(seconds)",9x,5x,"force in x",5x,"force in y",
     3 5x,"force in z",/,3x,13("="),9x,3(5x,10("="))    )
      do 40 loop=1,ntimes
      bfield(1)=0.
      bfield(2)=0.
      bfield(3)=0.
      time=t(loop)
c                       compute total b field from lamps
      do 30 nn=1,ntotal
      n=nn-1-nleft
      call simpson(intgrnd,sstart,sstop,nsteps,simp)
      bfield(1)=bfield(1)+simp(1)
      bfield(2)=bfield(2)+simp(2)
      bfield(3)=bfield(3)+simp(3)
   30 continue
c                       compute force from magnetic field on current
c                                as j x b
      tt=time-(s0+delayn0)/c
      temp=1.e-7 * cn0(0,tt)
      x=(dy0*bfield(3)-dz0*bfield(2))*temp
      y=(dz0*bfield(1)-dx0*bfield(3))*temp
      z=(dx0*bfield(2)-dy0*bfield(1))*temp
      force(1,loop)=x
      force(2,loop)=y
      force(3,loop)=z
      ftotal(loop)=sqrt(x*x + y*y + z*z)
      write(6,203) tt,x,y,z
  203 format(e15.5,10x,3e15.5)
   40 continue
      id="cathode "
   80 continue
      call exit
      end
```

```
      subroutine intgrnd(s,approx)
c==================================================================
c
c                                         #
c       #        #      #                #
c          # ## ###  ###  # ## # ##      #
c       #  ##  # #  #   # ##  # ## #  ## #
c       #  #   # #  #   # #    #   # #  ##
c       #  #   # #   ###  #    #   # #   #
c       #  #   # #   #    #    #   # #   #
c       #  #   # ##  ###  #    #   #  ####
c                   #   #
c                    ###
c
c                compute the integrand of equation (1)
c       --- include the image due to the planar reflector ---
c------------------------------------------------------------------
      dimension vn(3),approx(3),value(3)
      common /intgrl/ sdelta,x0,y0,z0,n,time
      data c/2.997925e8/
      image=0
      approx(1)=0.
      approx(2)=0.
      approx(3)=0.
      call rn(n,s,delayn,xn,yn,zn,dx,dy,dz)
      delay=(s+delayn)/c
    1 x=x0-xn
      y=y0-yn
      z=z0-zn
      value(1)=0.
      value(2)=0.
      value(3)=0.
      r=sqrt(x*x + y*y + z*z)
c                compute the vector direction   v
      vn(1)=(y*dz-z*dy)
      vn(2)=(z*dx-x*dz)
      vn(3)=(x*dy-y*dx)
      if(vn(1)*vn(1)+vn(2)*vn(2)+vn(3)*vn(3).eq.0.) goto 10
      vn(1)=vn(1)/r
      vn(2)=vn(2)/r
      vn(3)=vn(3)/r
c                compute the remaining part of the integrand
      tt=time-delay-r/c
      temp= - cn0(n,tt)/(r*r) - cn1(n,tt)/(c*r)
      value(1)=vn(1)*temp
      value(2)=vn(2)*temp
      value(3)=vn(3)*temp
   10 continue
      approx(1)=approx(1)+value(1)
      approx(2)=approx(2)+value(2)
      approx(3)=approx(3)+value(3)
   20 if(image.eq.1) return
```

```
image=1
zn=-zn
dx=-dx
dy=-dy
goto 1
end
```

```
      subroutine rn(n,s,delayn,xn,yn,zn,dx,dy,dz)
c=================================================================
c
c                      #
c                   #  #
c      # ##   ##   ### #          # ##  # ##
c      ##  # #  #   #  # ##       ##  # ##  #
c      #   #  ###   #  ##  #      #     #   #
c      #   # #  #   #  #   #      #     #   #
c      #   # #  #   #  #   #      #     #   #
c      ####   ## #  ## #   #      #     #   #
c      #
c      #
c
c     this subroutine defines the current channel
c-----------------------------------------------------------------
      dimension delayd(30)
      common /path/ nleft,nright,xend,xdip,yspace,zhght,zdip,delayd
c                      define path location as function of arc length s
      xn=(-1.)**n *(xend-s)
      yn=n*yspace
      zn=zdip
c                      define vector direction as d(rn)/ds
      dx= - (-1.)**n
      dy=0.
      dz=0.
c
      delayn=delayd(1 + n + nleft)
      if(zdip.eq.zhght) return
c                 curve the ends up to zhght - - parabola - -
      xx1=abs(xn)-xdip
      if(xx1.le.0.) return
      xx2=xend-xdip
      zn=zn+(zhght-zdip)*
     1  xx1**2/xx2**2
      dz=-2.*(zhght-zdip)*xx1/xx2**2
      dr=sqrt(dx*dx+dz*dz)
      dx=dx/dr
      dz=dz/dr
      if(s.gt.xend) dz=-dz
      return
      end
```

```
      subroutine simpson(f,q0,q2n,twon,simp)
c=====================================================================
c
c
c             #
c       ###      ### ##  # ##   ###   ###  # ##
c      #      #  #  #  # ##  # #     #   # ##  #
c       ###   #  #  #  # #   #  ###  #   # #   #
c          #  #  #  #  # #   #     # #   # #   #
c      #   #  #  #  #  # #   # #   # #   # #   #
c       ###   #  #  #  # ####   ###   ###  #   #
c                        #
c                        #
c
c---------------------------------------------------------------------
      integer twon
      dimension simp(3),even(3),odd(3)
      nm1=twon/2.-1
      qdelta=(q2n-q0)/float(twon)
c                        include the two endpoints according to simpson
      call f(q0,even)
      call f(q2n,odd)
      simp(1)=even(1)+odd(1)
      simp(2)=even(2)+odd(2)
      simp(3)=even(3)+odd(3)
c                        include the center points according to simpson
      do 30 loop1=1,nm1
      qe=q0+2.*loop1*qdelta
      qo=qe-qdelta
      call f(qo,odd)
      call f(qe,even)
      simp(1)=simp(1)+2.*even(1)+4.*odd(1)
      simp(2)=simp(2)+2.*even(2)+4.*odd(2)
      simp(3)=simp(3)+2.*even(3)+4.*odd(3)
   30 continue
c      .           include the last odd indexed point (missed in loop1)
      qo=qe+qdelta
      call f(qo,odd)
      simp(1)=(4.*odd(1)+simp(1) )*qdelta/3.
      simp(2)=(4.*odd(2)+simp(2) )*qdelta/3.
      simp(3)=(4.*odd(3)+simp(3) )*qdelta/3.
      return
      end
```

```
c======================================================================
c
c     #
c    # #                    #   #
c    #   #   # # ##    ###  ###      ###  # ##   ###
c   ###  #   # ##  # #   #  #   #  #   # ##  # #
c    #   #   # #   # #      #   #  #   # #   #  ###
c    #   #   # #   # #      #   #  #   # #   #     #
c    #   #  ## #   # #   #  #   #  #   # #   # #   #
c    #    ## # #   #  ###   ##  #   ###  #   #  ###
c
c
c
c        define the current and its time derivative
c                 --- for lamp #n ---
c---------------------------------------------------------------------
      function cn0(n,t)
      common /source/ t1,t2,peak,c
c               current source time dependence
      cn0=0.
      tt=t-0./c
      if(tt.lt.0.) return
      cn0=peak*(exp(-tt/t1)-exp(-tt/t2))
      return
      end
c
c
      function cn1(n,t)
      common /source/ t1,t2,peak,c
c               d by dt of current source time dependence
      cn1=0.
      tt=t-0./c
      if(tt.lt.0.) return
      cn1=-peak*(exp(-tt/t1)/t1 - exp(-tt/t2)/t2)
      return
      end
```